Nonlinear Compensation for High Performance Feedback Systems with Actuator Imperfections

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Outline

- Large feedback control
- Control application comparison
  - Micro-Precision Interferometer (NASA-JPL)
    - large feedback with expensive actuators
  - Motion control of 2-DOF parallel robots (UW)
    - large feedback with inexpensive actuators
- Nonlinear Dynamic Compensation
  - Gain-Decreasing
  - Gain-Increasing
  - Parallel Loop Recovery
  - Parallel Loop Recovery with Quiescent Compensation
- Experimental results
- Conclusions

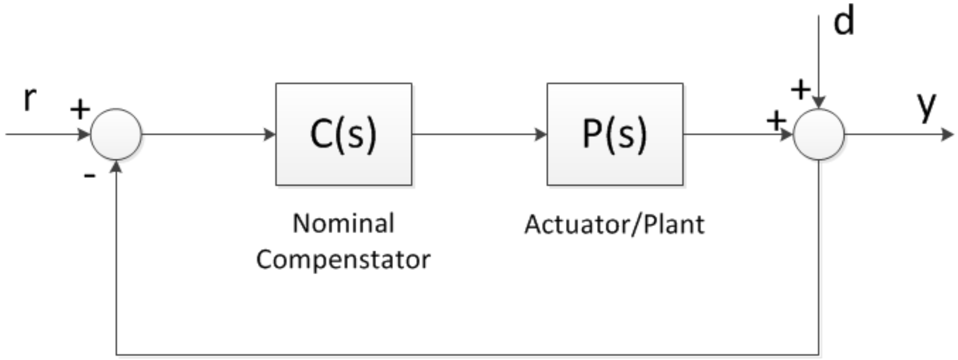
High Performance Control

- Frequency Domain Characterization
  - *Large disturbance rejection*
  - Very accurate tracking to high frequency
  - Reduction in sensitivity of the response to slight variations in the plant
- Time Domain Characterization
  - Transient response
    - Fast rise, settling times
    - Limited overshoot
  - Steady state response
    - Limited steady state error
- PID is often acceptable using time-domain measures of performance, but provides limited disturbance rejection because of small *feedback*

Feedback

- Loop Transmission $T(s) = C(s)P(s)$
- Return Difference $F(s) = 1 + C(s)P(s)$

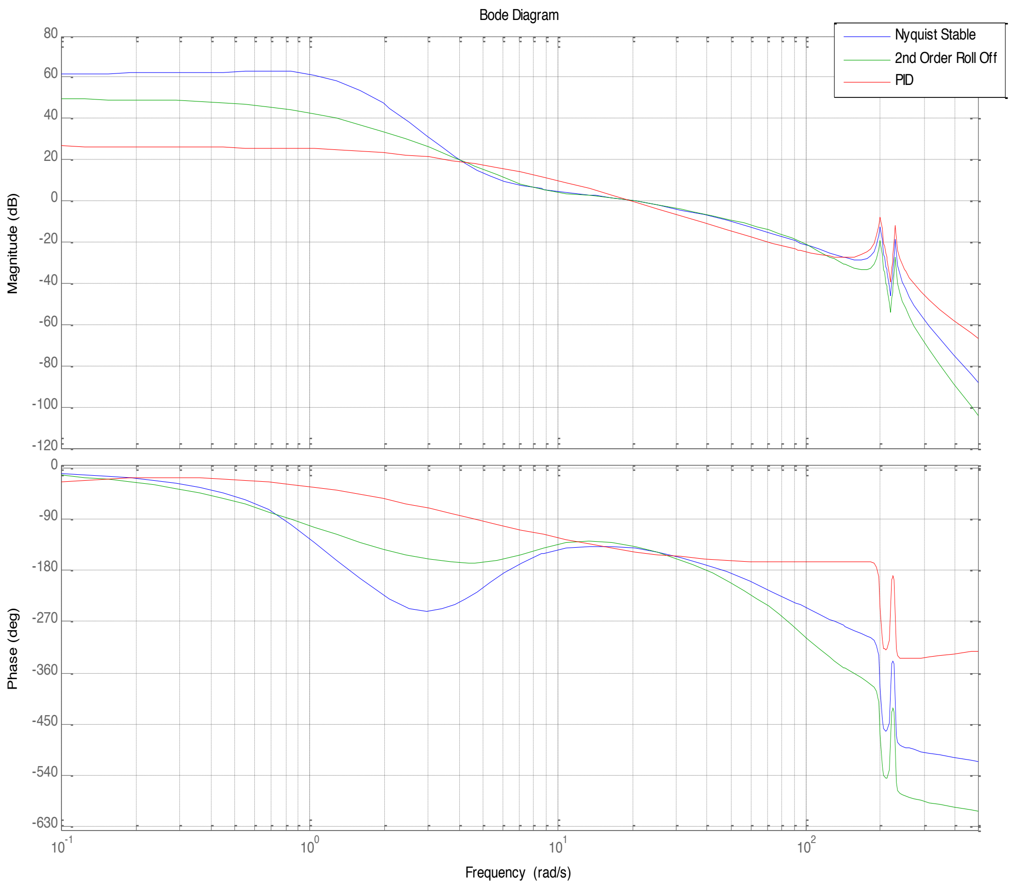
- Feedback $|F|$
  - Negative $|F| > 1$
  - Positive $|F| < 1$
  - Negligible $|T| << 1$
  - Large $|F| >> 1$



- Large Feedback
  - Disturbance rejection $\frac{y(s)}{d(s)} = \frac{1}{1 + C(s)P(s)}$ Low magnitude
  - Reference tracking $\frac{y(s)}{r(s)} = \frac{C(s)P(s)}{1 + C(s)P(s)}$ Magnitude ~1

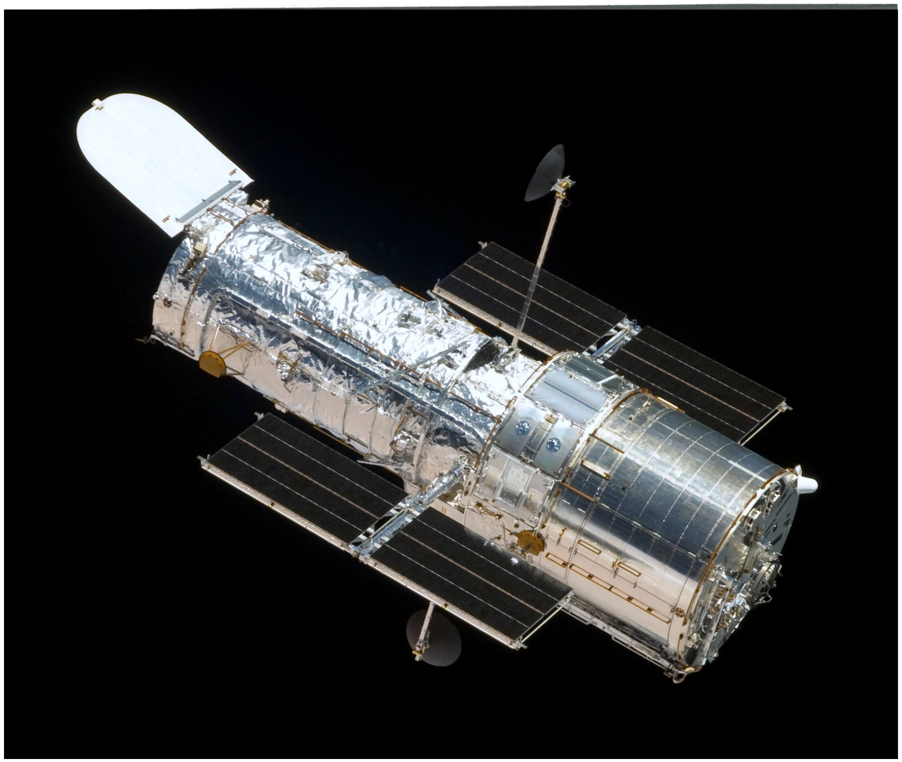
Control Goal

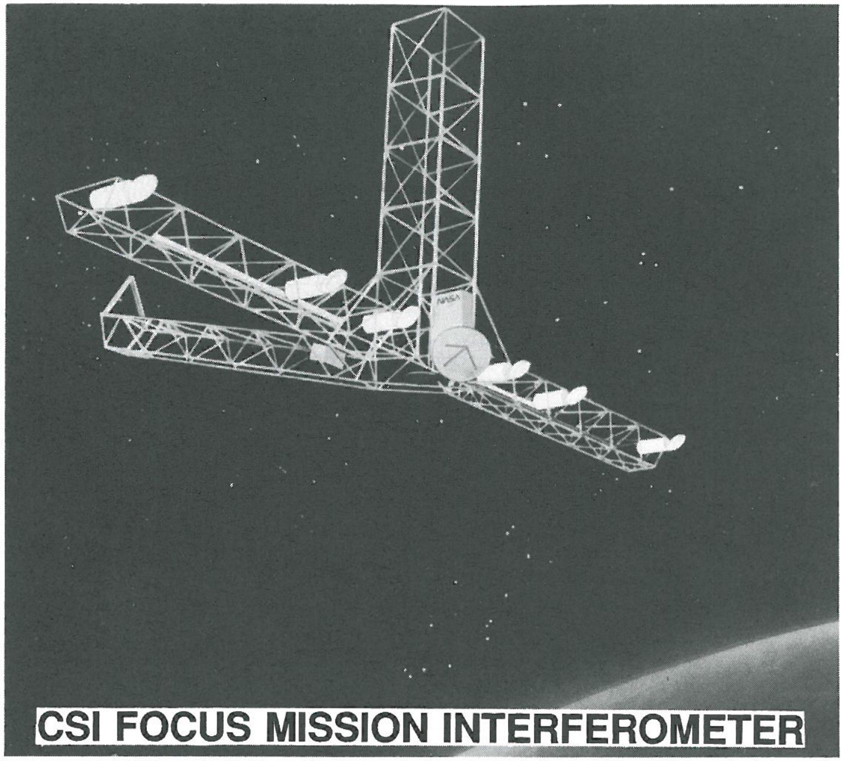
- Definitions
  - Large feedback: $|F| >> 1$
  - Bandwidth: $\omega_b \ \ where |T(j\omega_b)| = 1$
  - Functional Bandwidth: $\omega_f \ \ where \ |T(j\omega)| \approx A_0 \ \forall \omega \leq \omega_f$
  - *Nyquist-Stable* system rolls –off steeper than -12 dB/oct



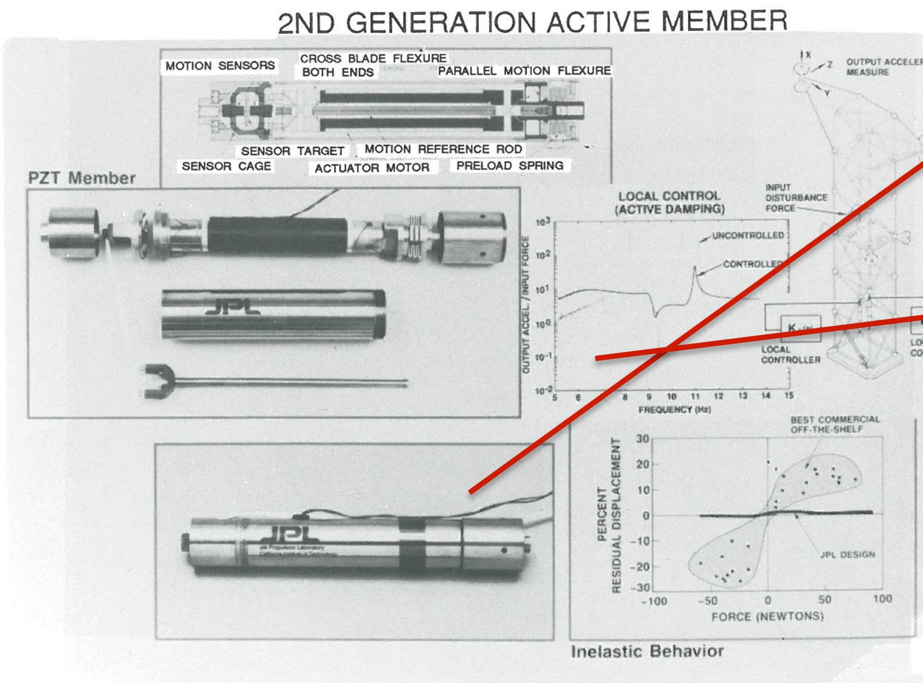
- Goal
  - Large feedback across functional bandwidth subject to established bandwidth limit

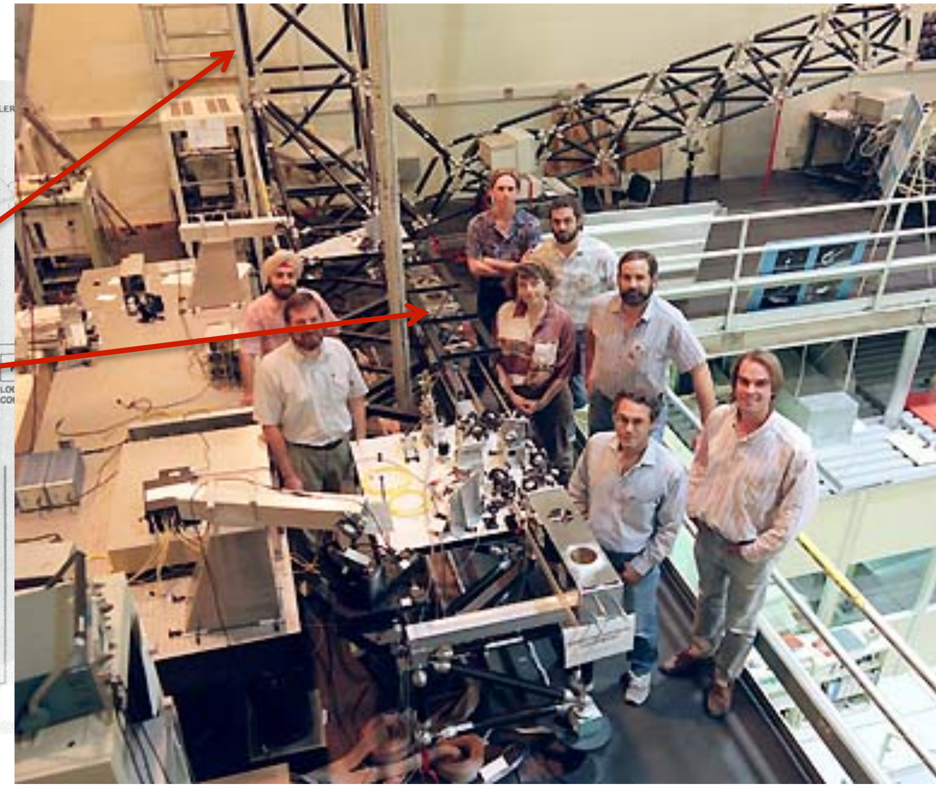
Application of Large Feedback Control



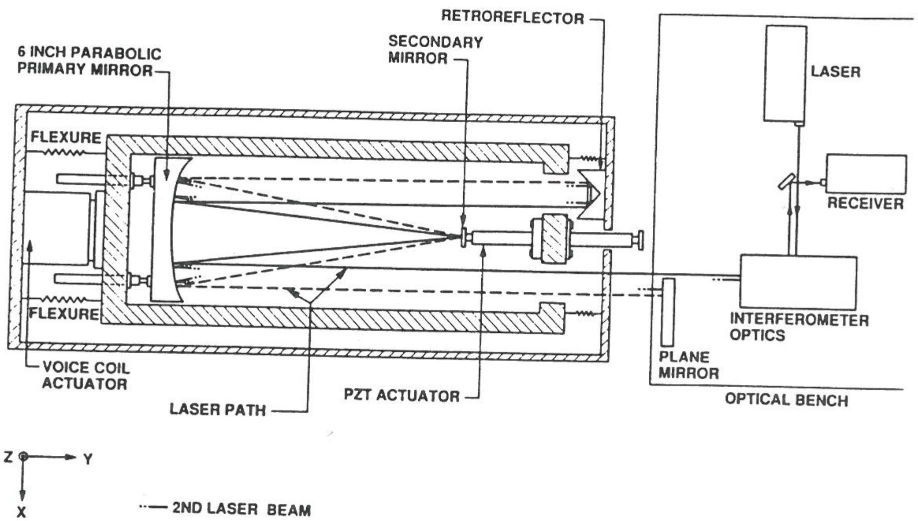


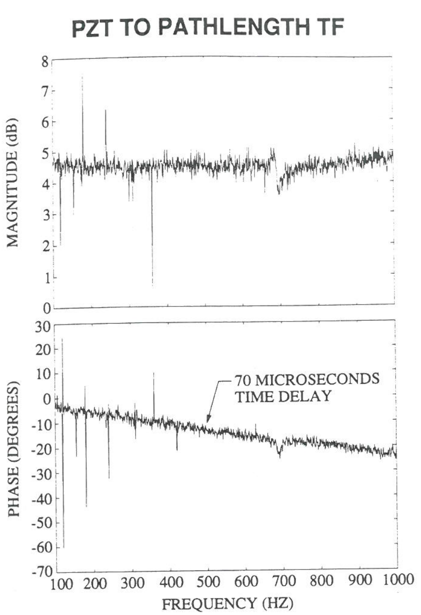
Actuators for Large Feedback

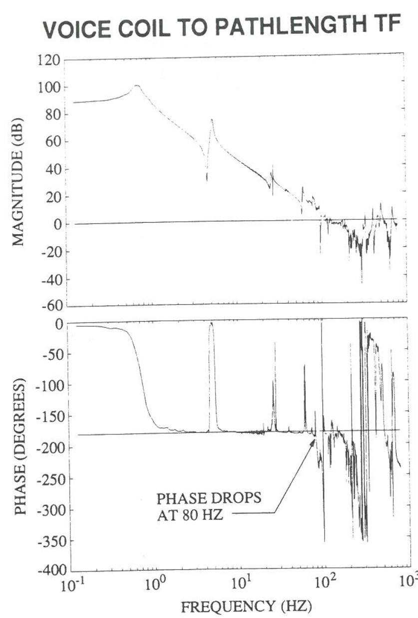




Large Feedback Loop Transmission







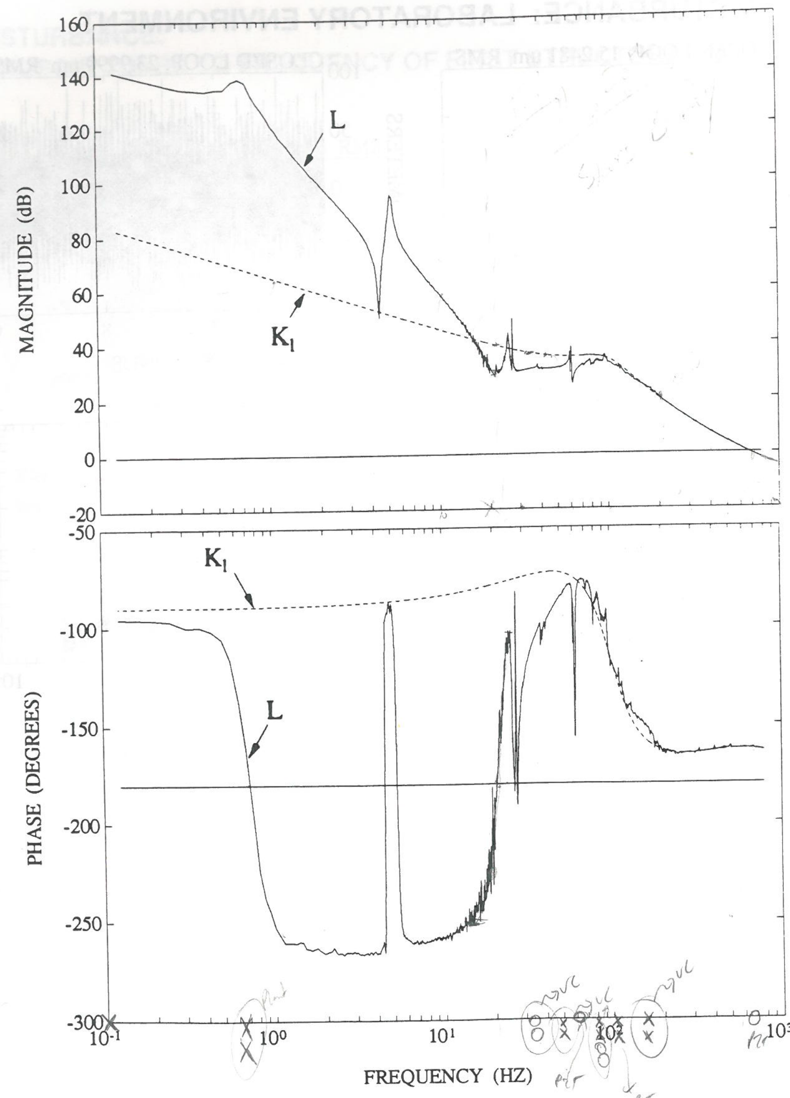
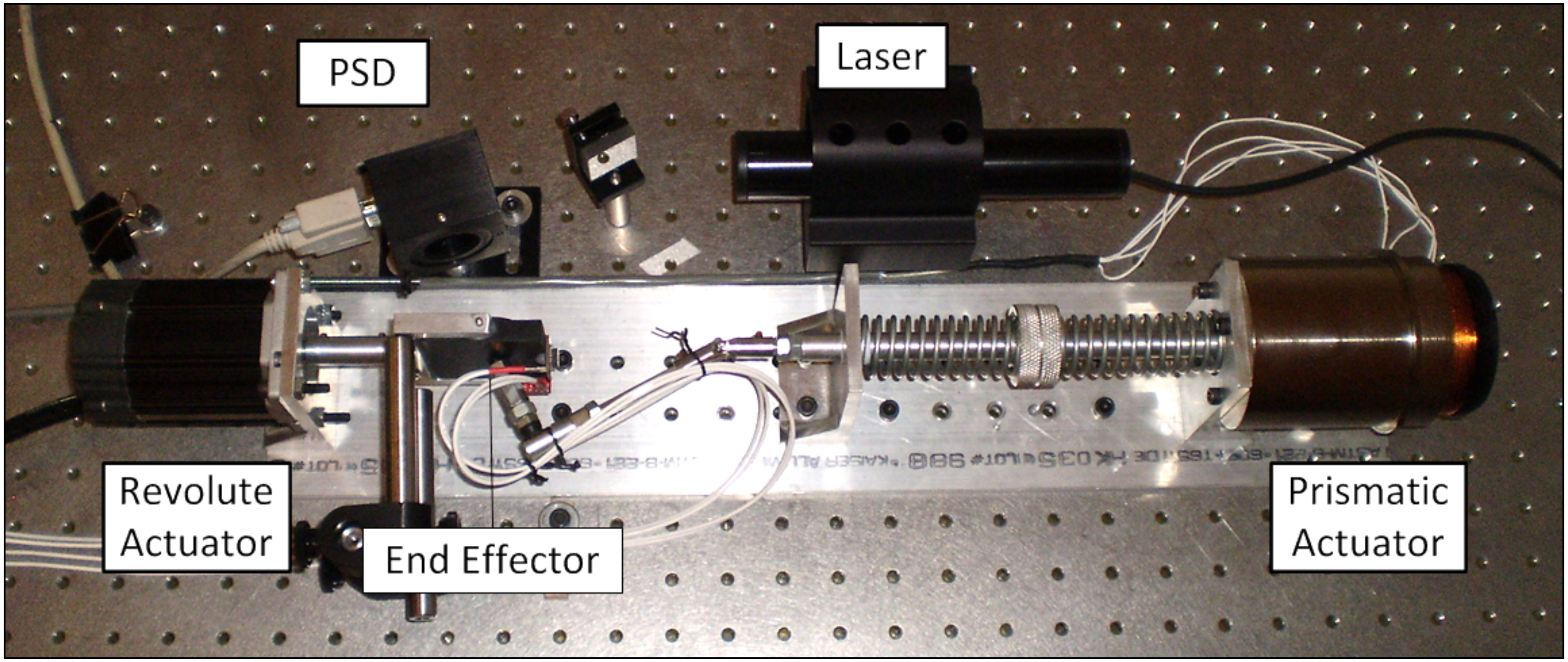


Figure 8. PZT and Total Loop Gain and Phase

Why are High-Performance Feedback Systems So Rarely Implemented?

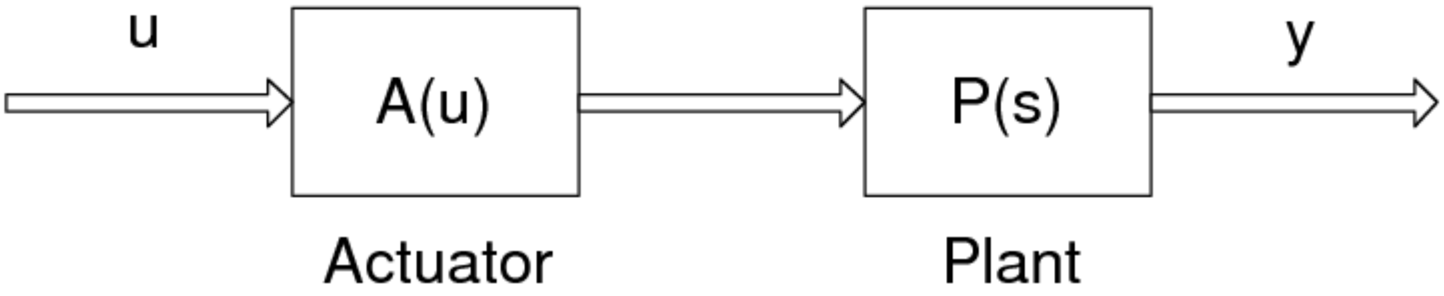
- Increased design complexity
- Insufficient motivation to implement
  - “High-Performance” is not needed
  - |F| is not a desirable measure of performance
  - |F| not quantifiable or known
  - Risk outweighs the rewards
    - Feedback system very sensitive to variations in loop transmission
- Feedback limitations
  - Sluggish/weak actuator
  - Actuator is sufficiently powerful but ***imperfect***
  - Sensor dynamics/noise
  - Plant model infidelity/uncertainty
  - Non-minimum phase
  - Nonlinearities (not related to actuator imperfection)

Large Feedback Using an Imperfect Actuator?



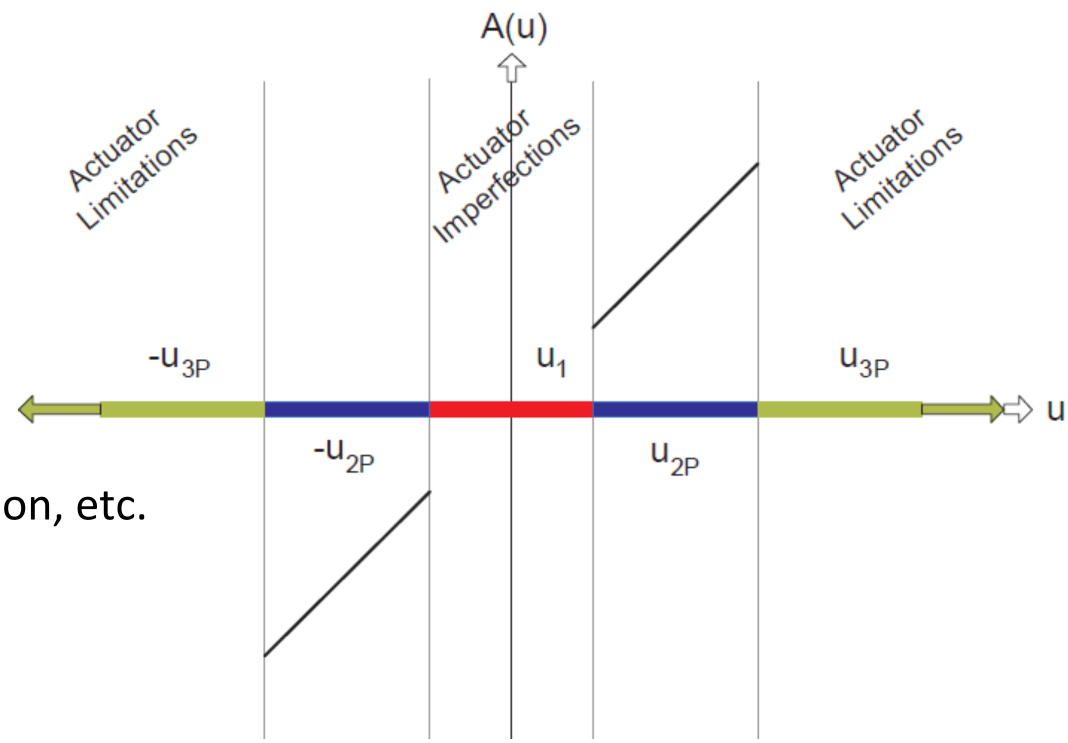
- Two Rotational Degrees of Freedom
- Decoupled Axes
- Inexpensive, Easily Manufactured
- Rugged (military application)
- Imperfect Actuator
  - Multiple uncertain nonlinearities
- Substantial Disturbance Rejection Required

System to Be Controlled, Cascade Decomposed



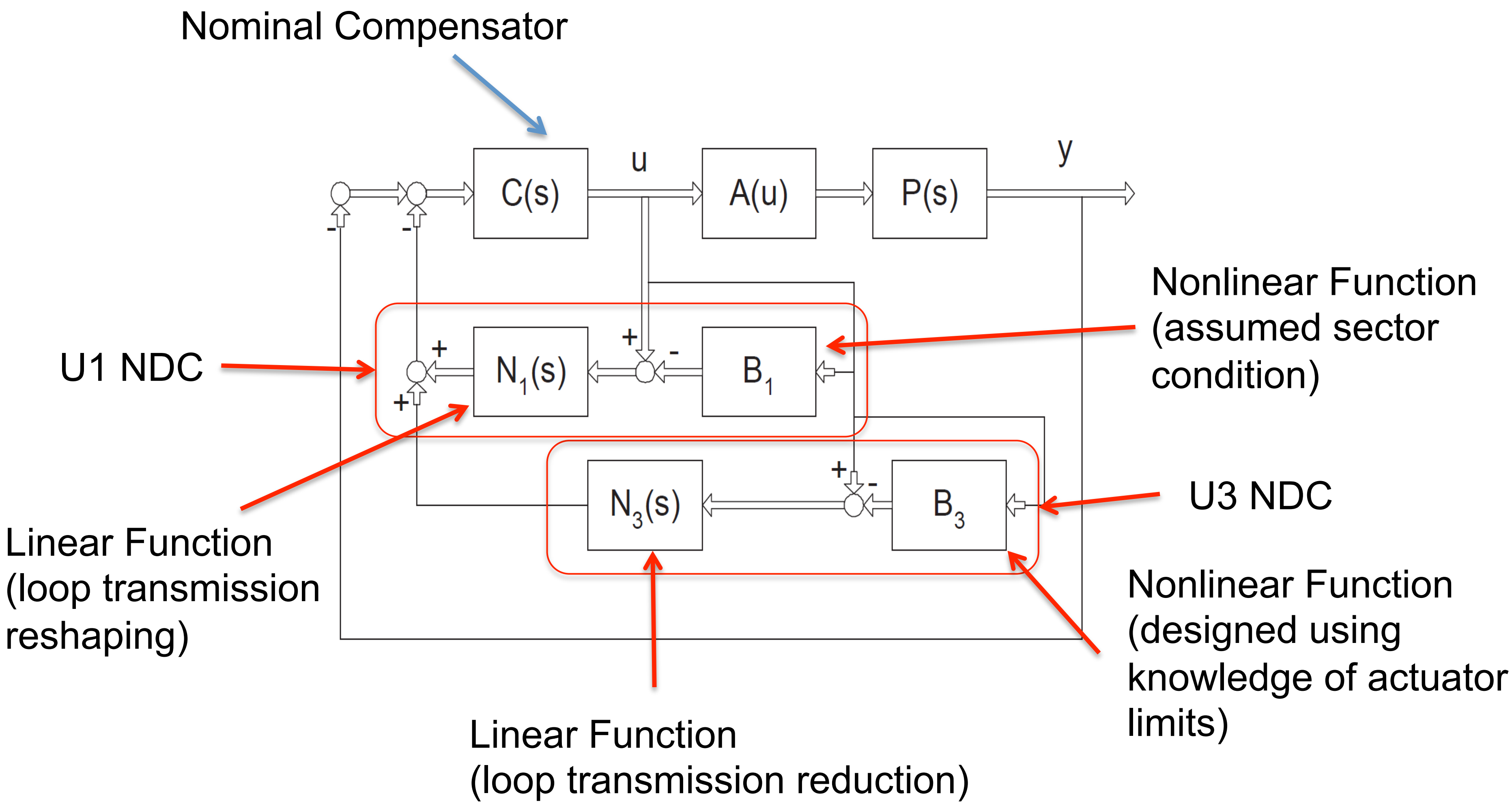
LIID Systems

- Linear on an Interior Input Domain
  - Linear on a subset of inputs
  - Nonlinearities
    - High amplitude saturation
      - Easy to model
    - Low amplitude stiction, friction, etc.
      - Much more difficult to accurately model



- Goal
  - Develop a control architecture that delivers large feedback on LIID systems

Nonlinear Dynamic Compensation for Non-Linearities



Function of NDC

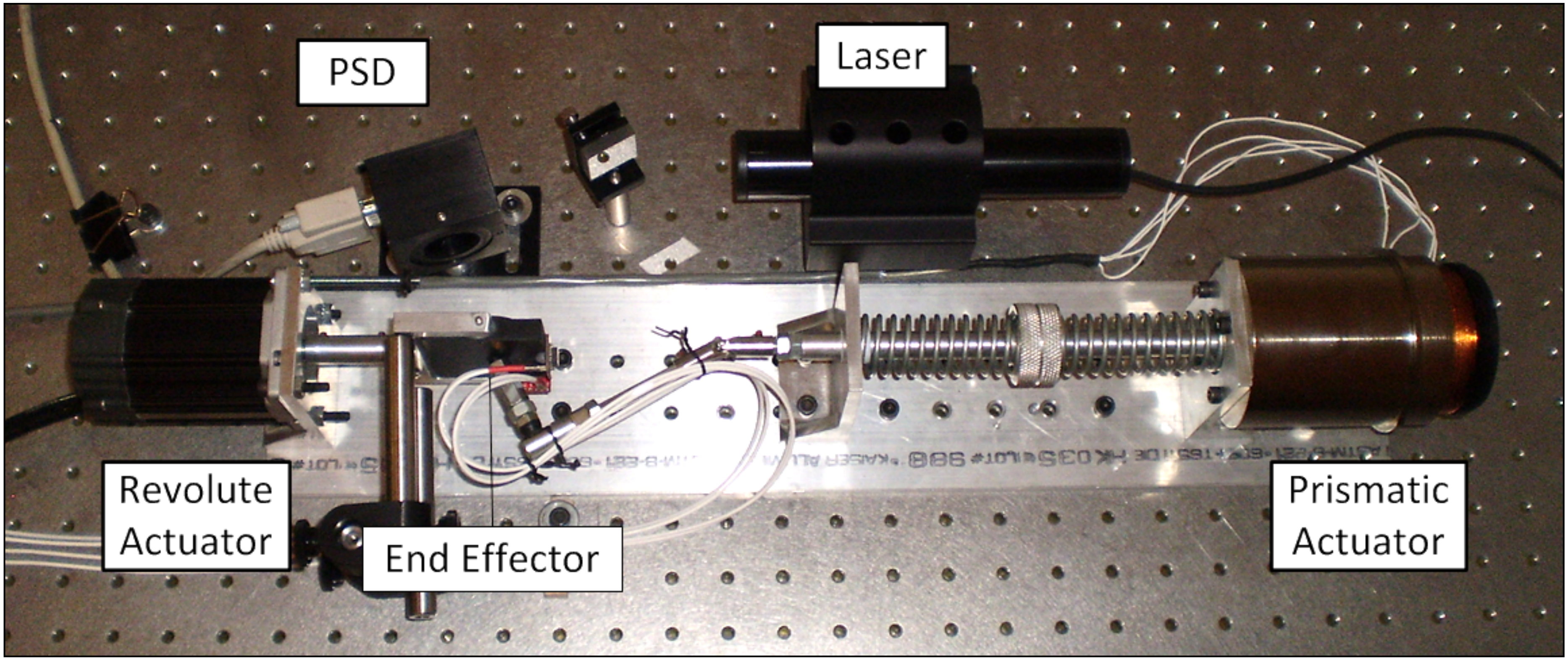
- U3 NDC
  - Retain stability when actuator is overdriven
  - Necessarily a loop modulus *reduction* function
- U1 NDC
  - Retain stability when actuator is influenced by small-signal nonlinearities

– [illegible] Quiescent Compensation (PLRQC)

– [illegible] application of absolute stability theory

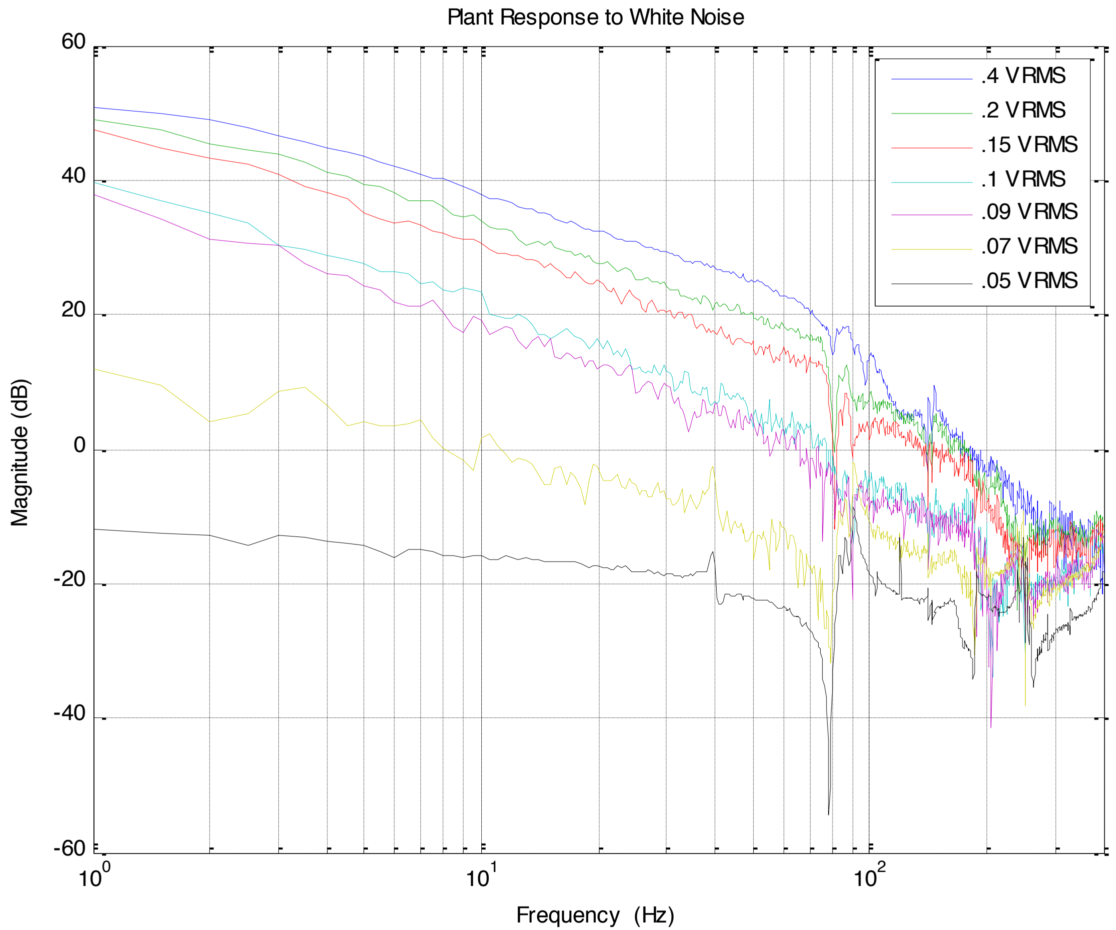
– [illegible] amplitude [illegible]

Experimental Verification



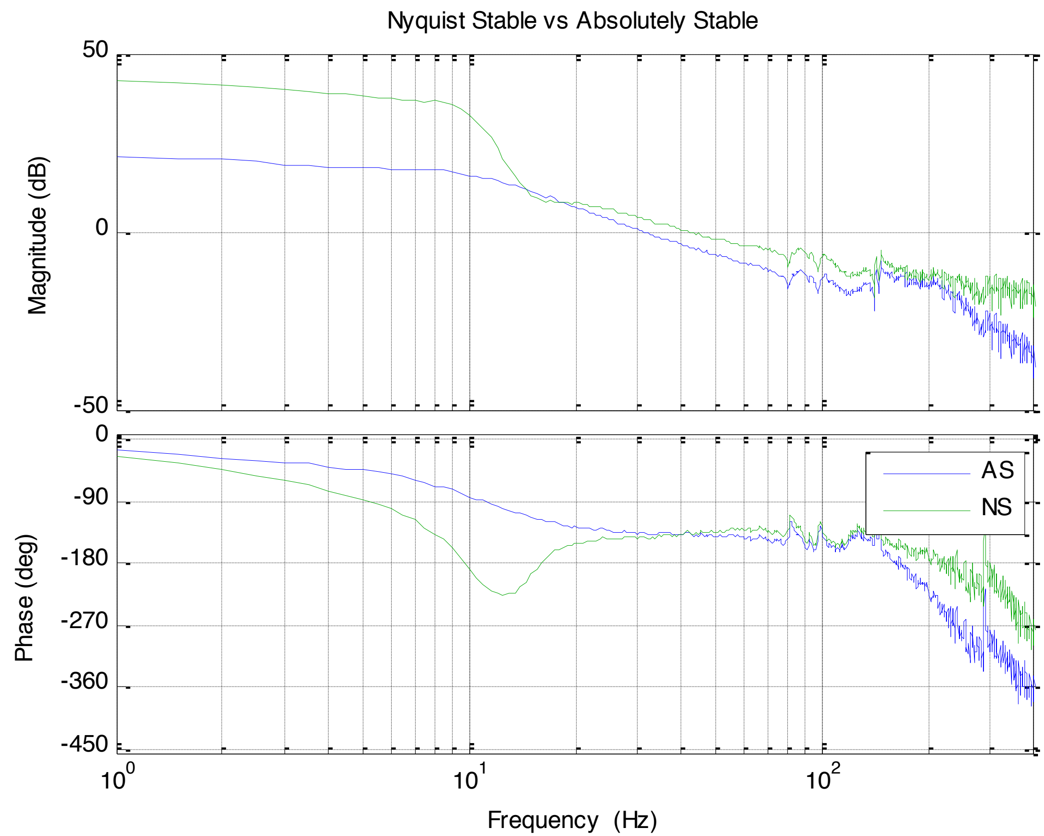
Plant Identification

- .4 VRMS represents nominal response of the plant
  - Modeled with 19th order transfer function
- Significant reduction in plant response at after .15 VRMS
- Change in shape of response below .09 VRMS
- Nonlinear phenomena dominating the response at very low variance

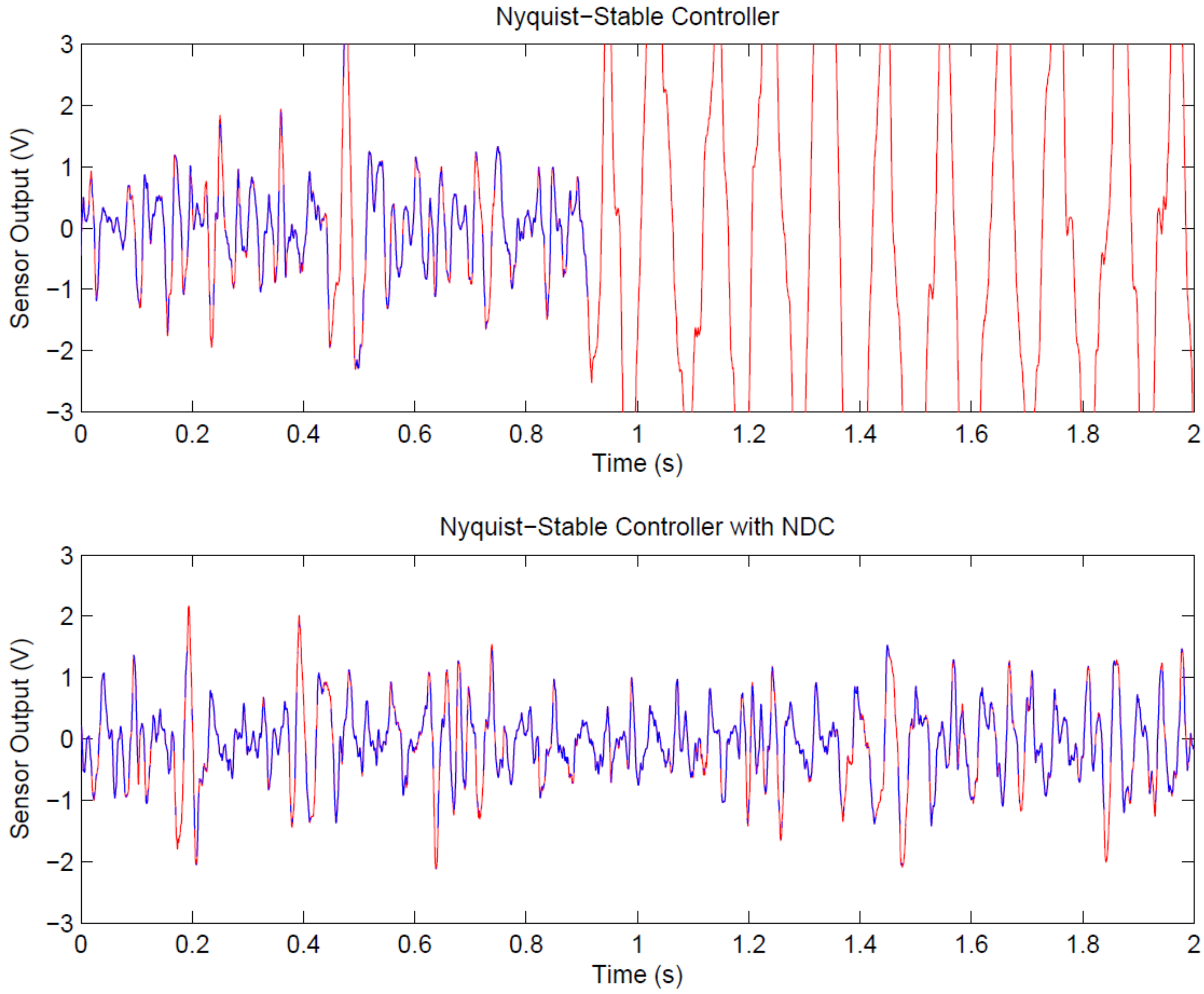


GDNDC/GINDC

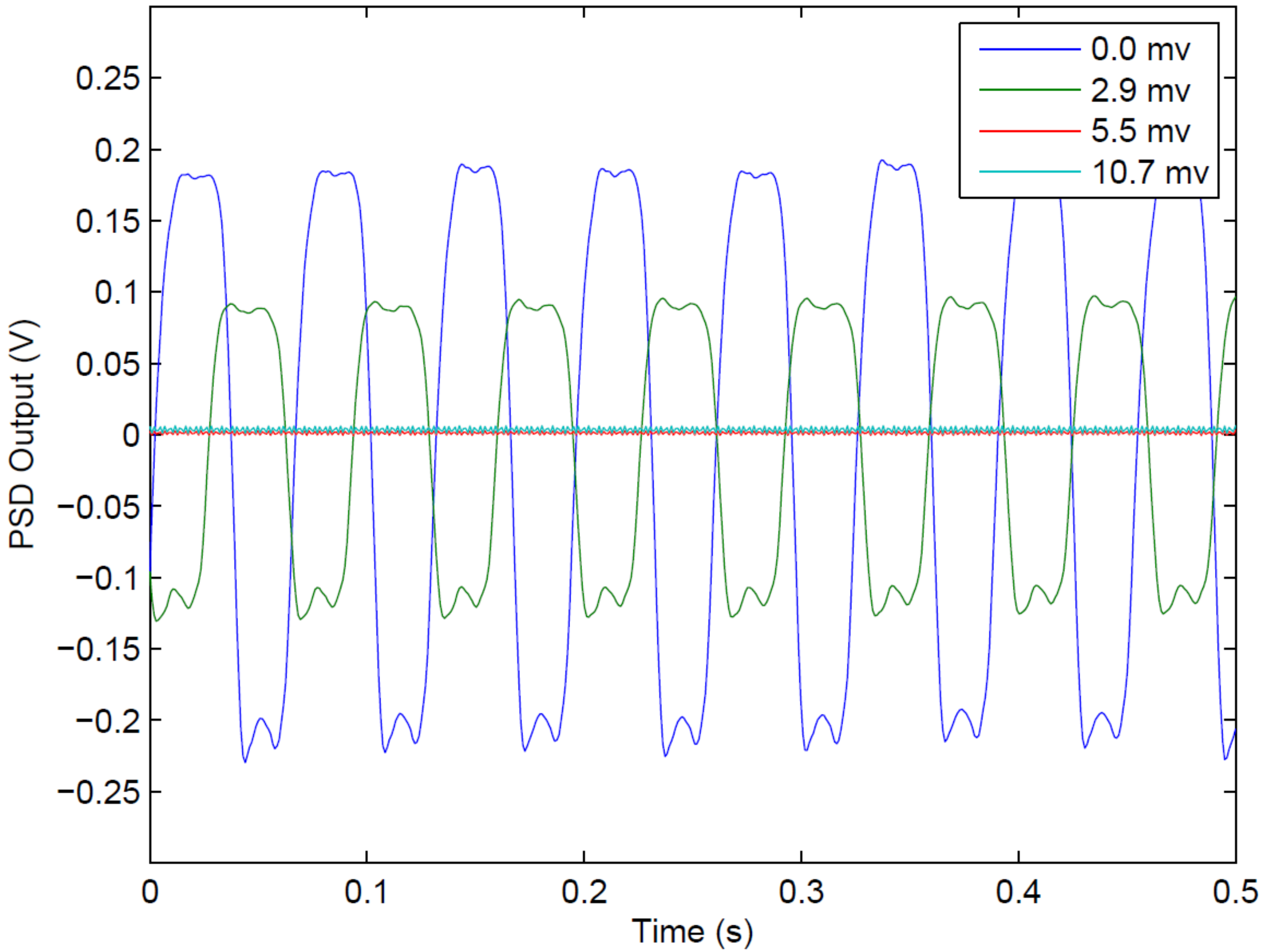
- Absolutely Stable System
  - 7th Order Controller
  - Satisfies Popov for sector [0,1]
- Nyquist-Stable System
  - 7th Order Controller
  - 20dB greater feedback across functional BW compared to AS
- GDNDC
  - Reshapes Nyquist-Stable loop shape to Absolutely Stable in U1 and U3
- GINDC
  - Reshapes Nyquist-Stable loop shape to Absolutely Stable in U3
  - Reestablishes Nyquist-Stable shape in U1 (employing a plant model found with one frequency response function)



Time Response in U3

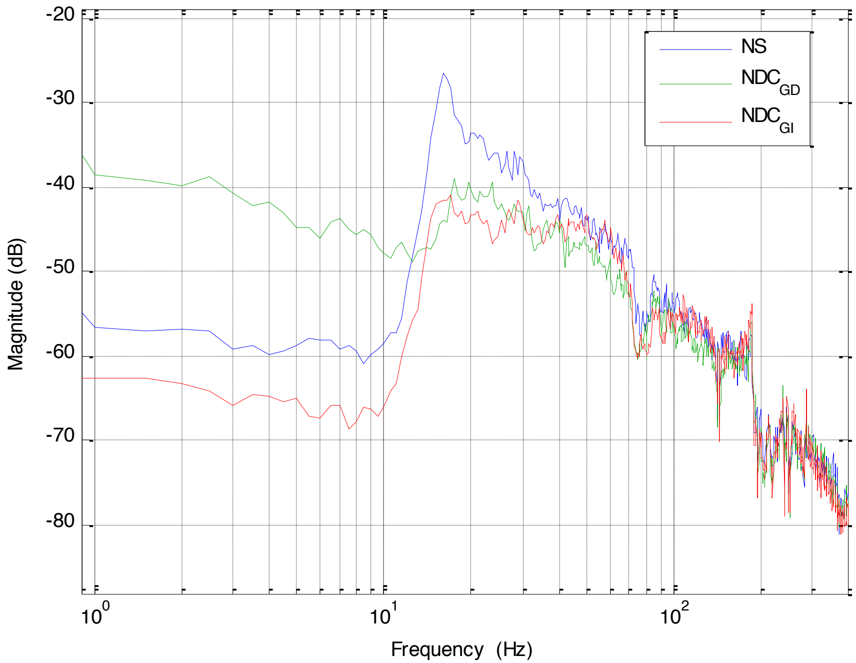


Time Response in U1

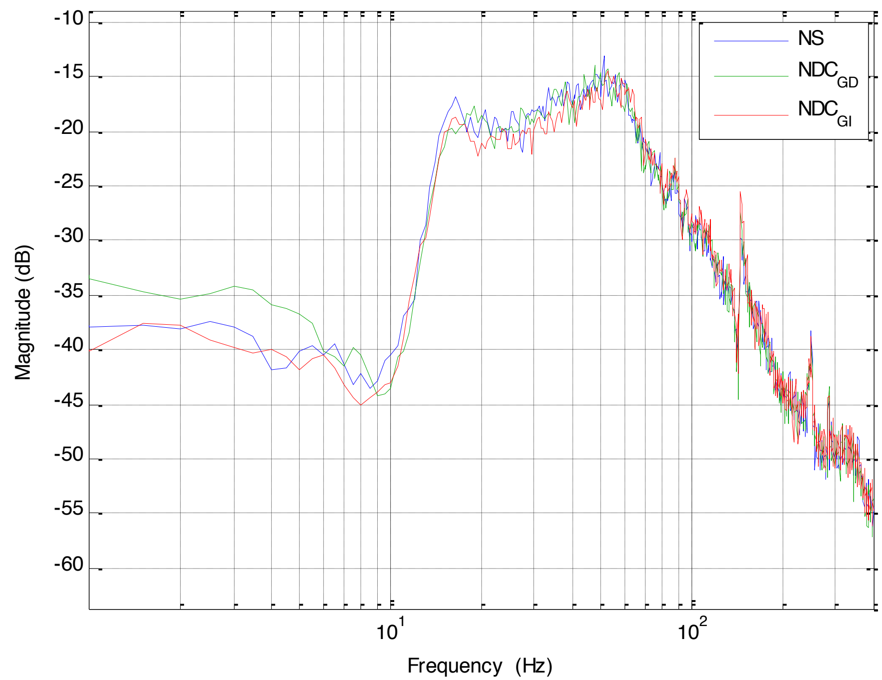


GD/GINDC Performance

Low Amplitude Disturbance



Nominal Amplitude Disturbance

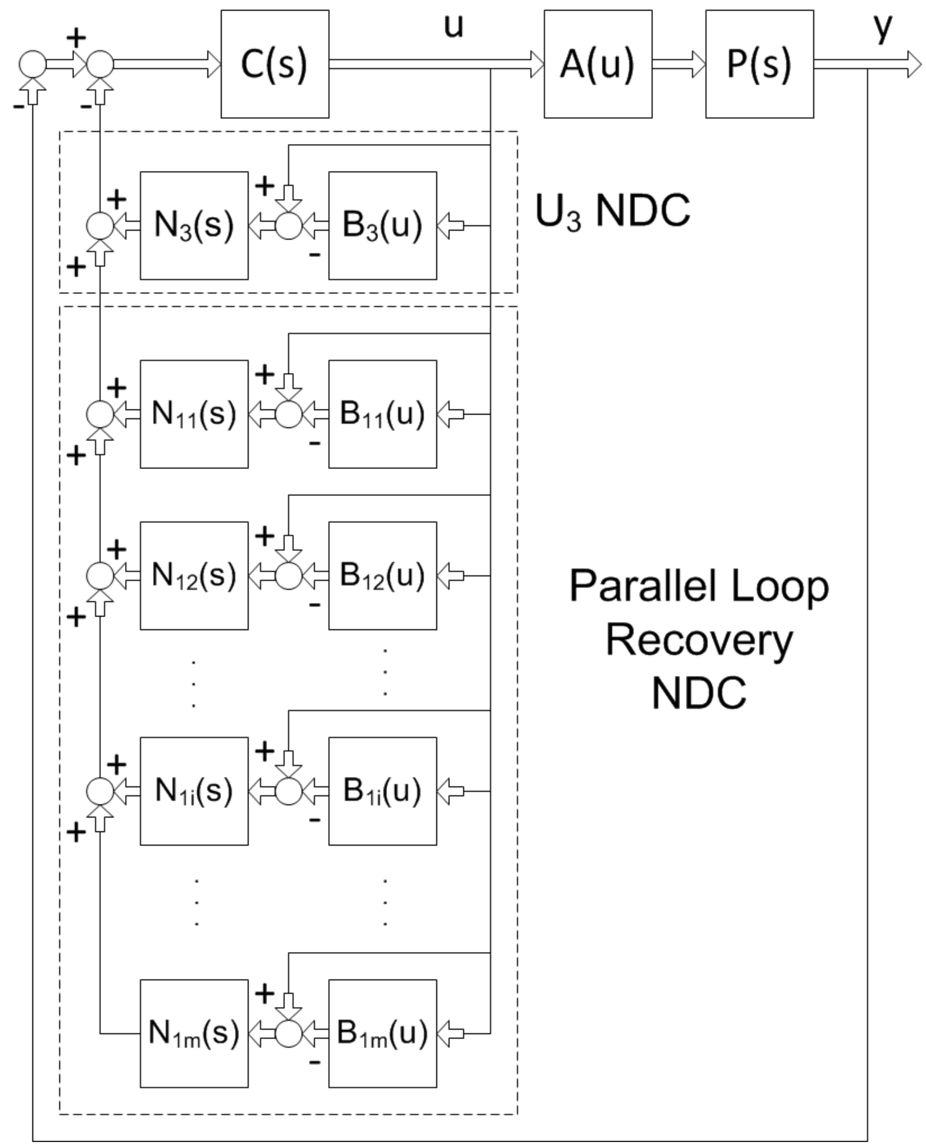


- GINDC delivers greater disturbance rejection over the functional BW
- No oscillation at 16Hz
- Increase in *positive feedback* at higher frequencies
  - More negative feedback
  - Can get “peaky” in certain disturbance environments

- GINDC and NS convergence
- 20 dB better performance across function BW compared to ASFG

Parallel Loop Recovery

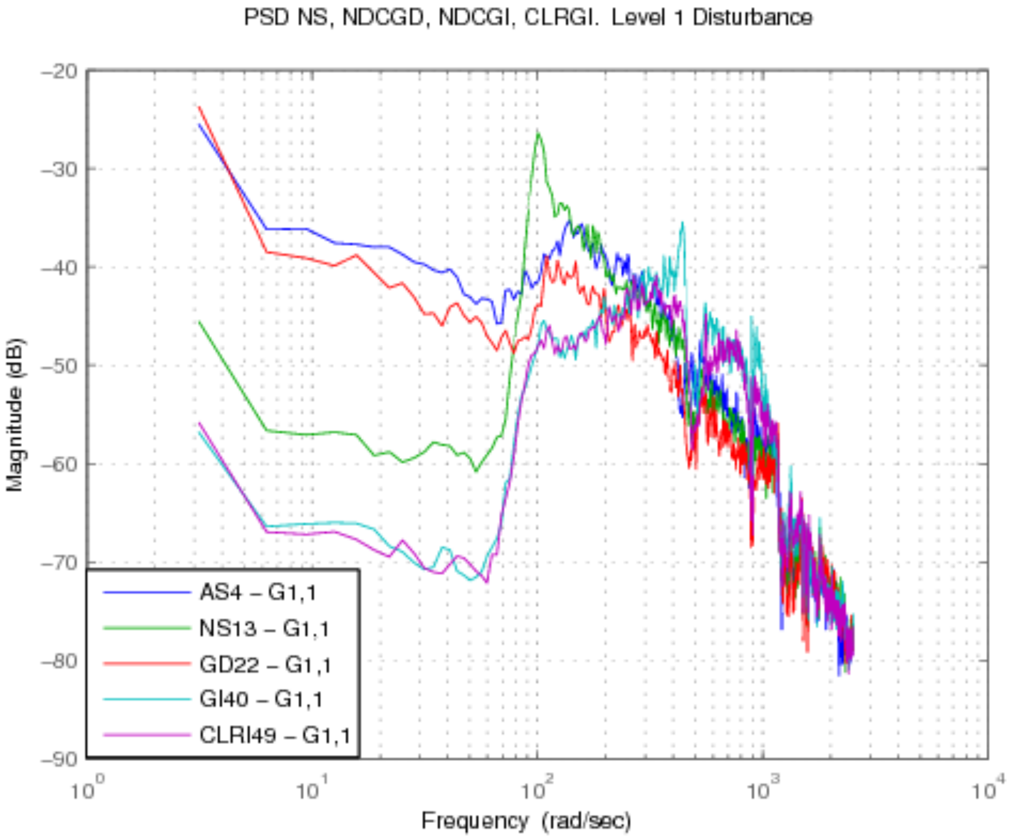
- Multiple plant models using a family of U1 frequency response functions
- A more accurate reshaping of the Nyquist Stable loop transmission is achieved



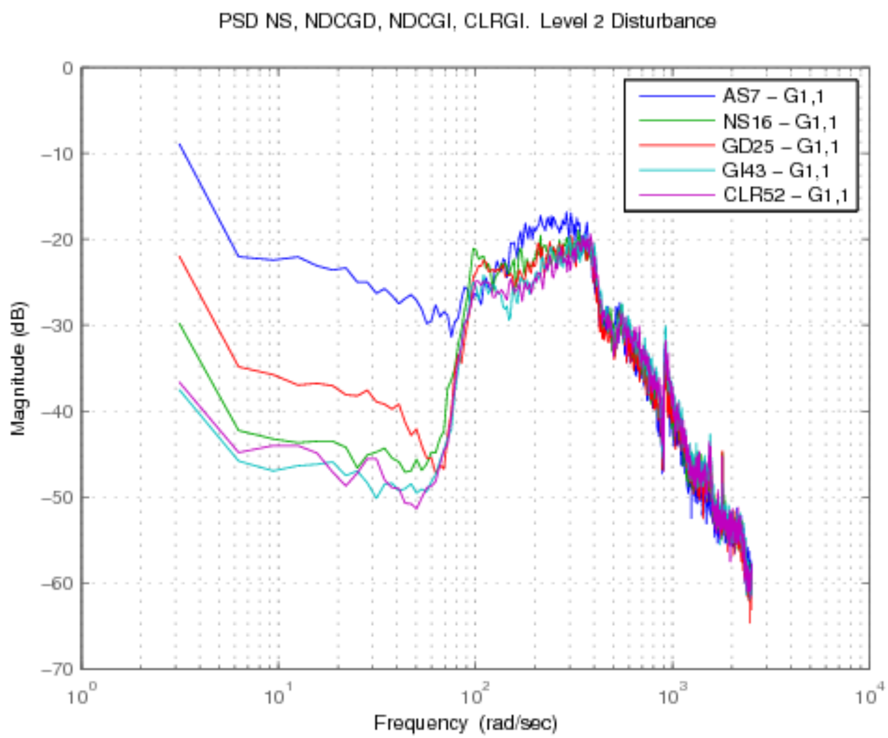
Disturbance Levels

- Gaussian White Noise Disturbances
- Level 0-1
  - Low variance (Level 0 variance less than Level 1)
  - Generates control signals in U1
- Level 2
  - Generates control signals in U1 and U2
- Level 3
  - Nominal disturbance environment
  - Generates control signals principally in U2
- Level 4
  - High variance
  - Control signal frequently exceeds actuator limit

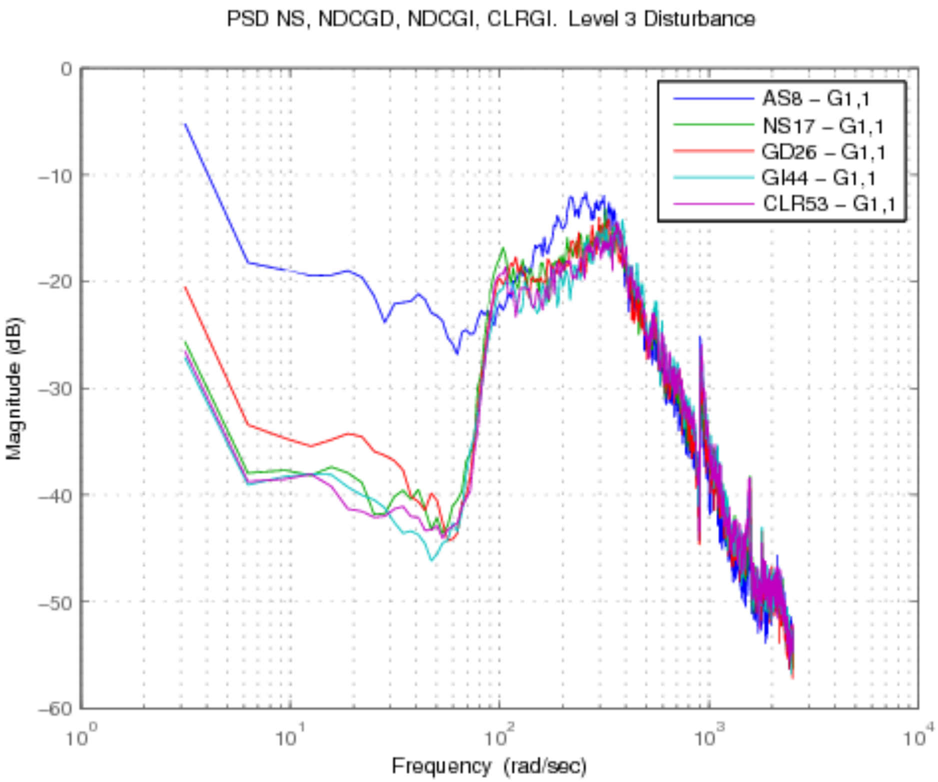
Level 1 Disturbance



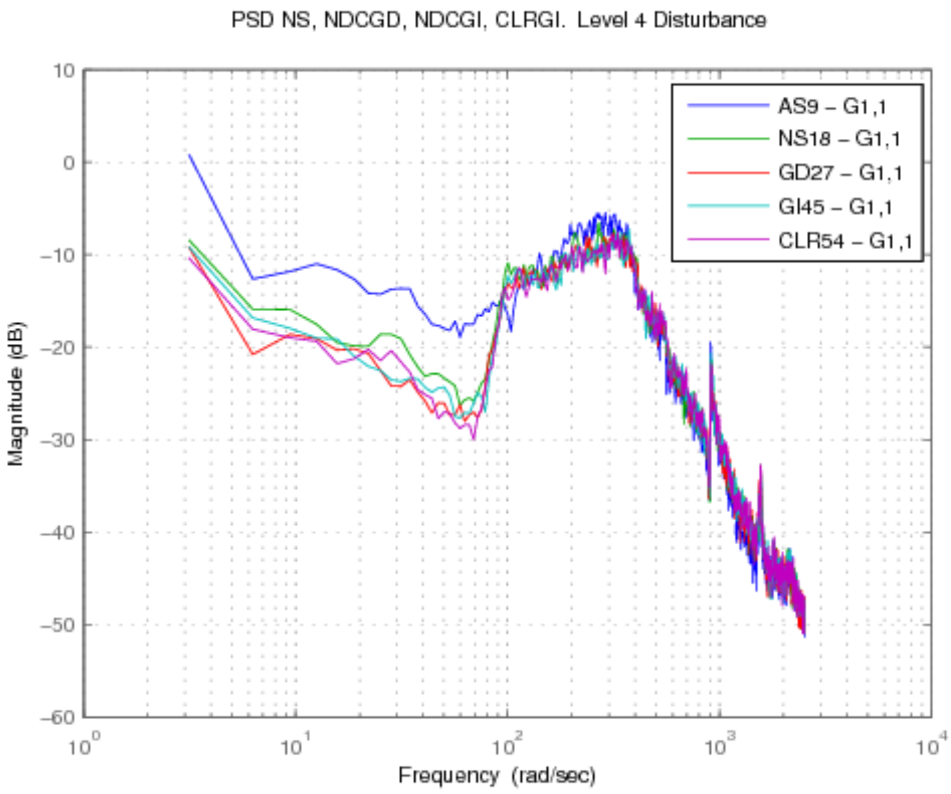
Level 2 Disturbance



Level 3 Disturbance

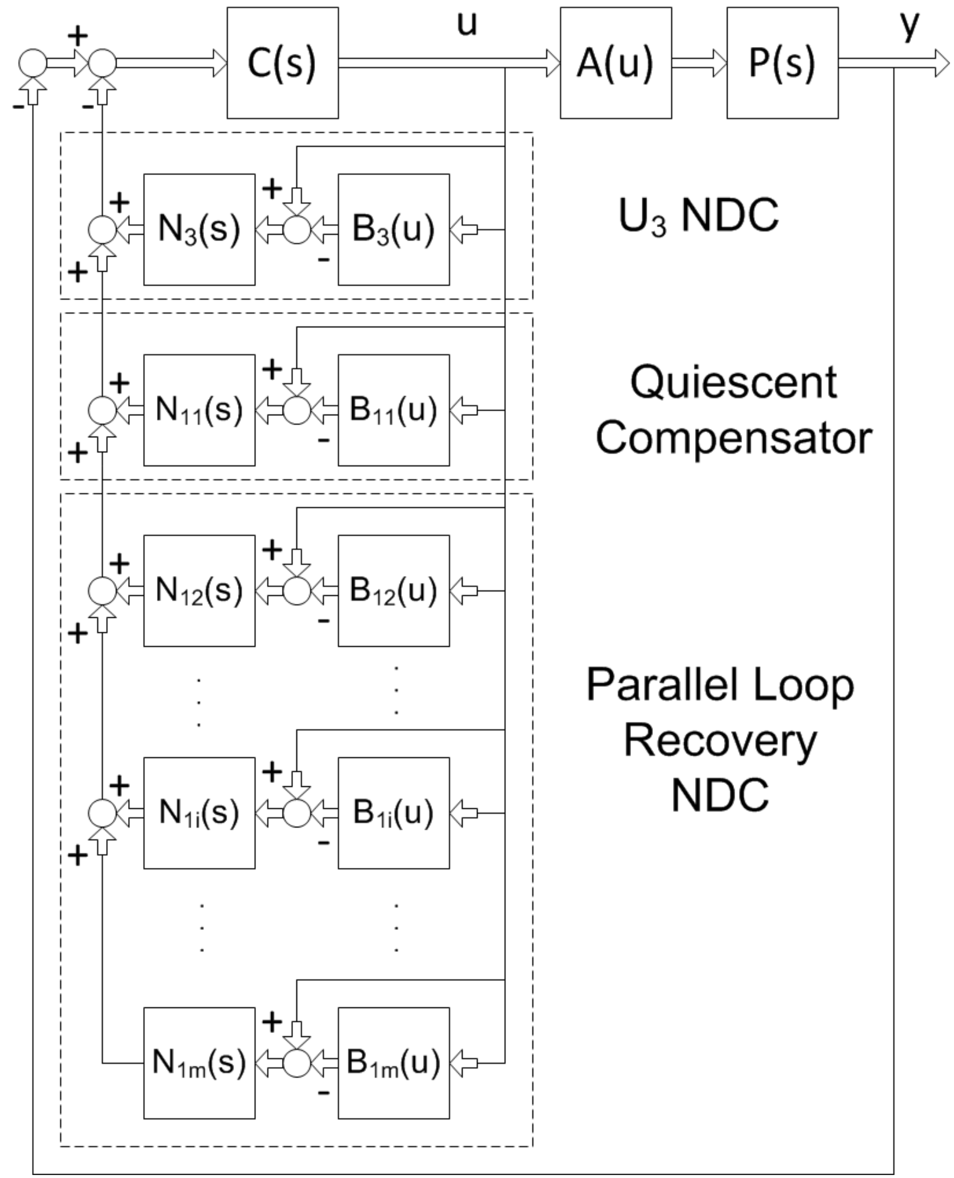


Level 4 Disturbance

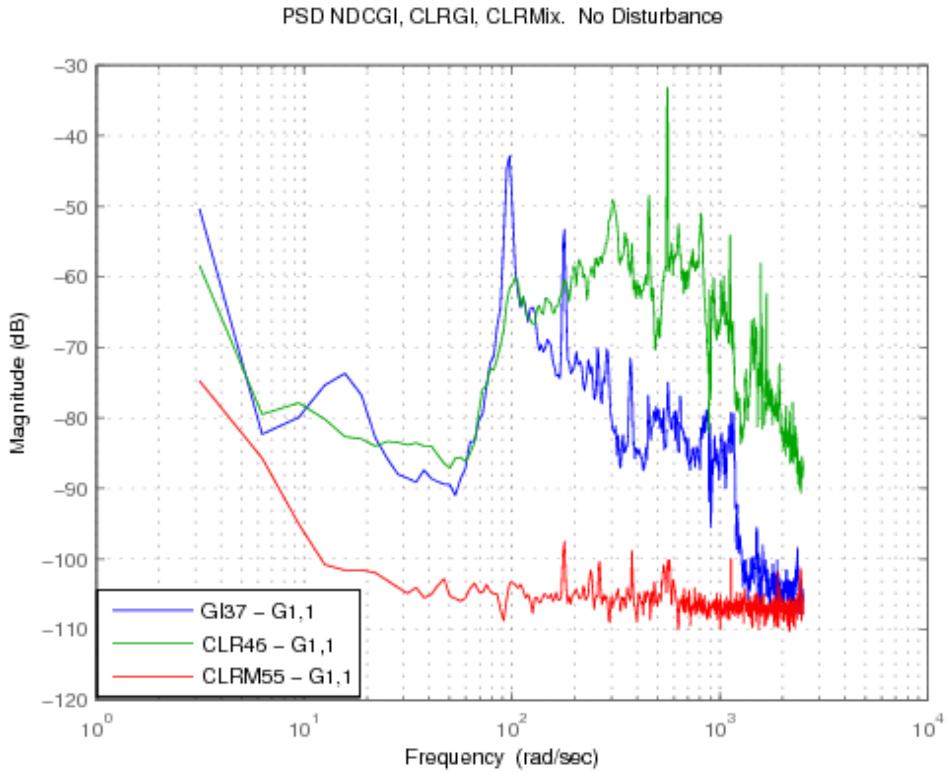


PLR with Quiescent Compensation

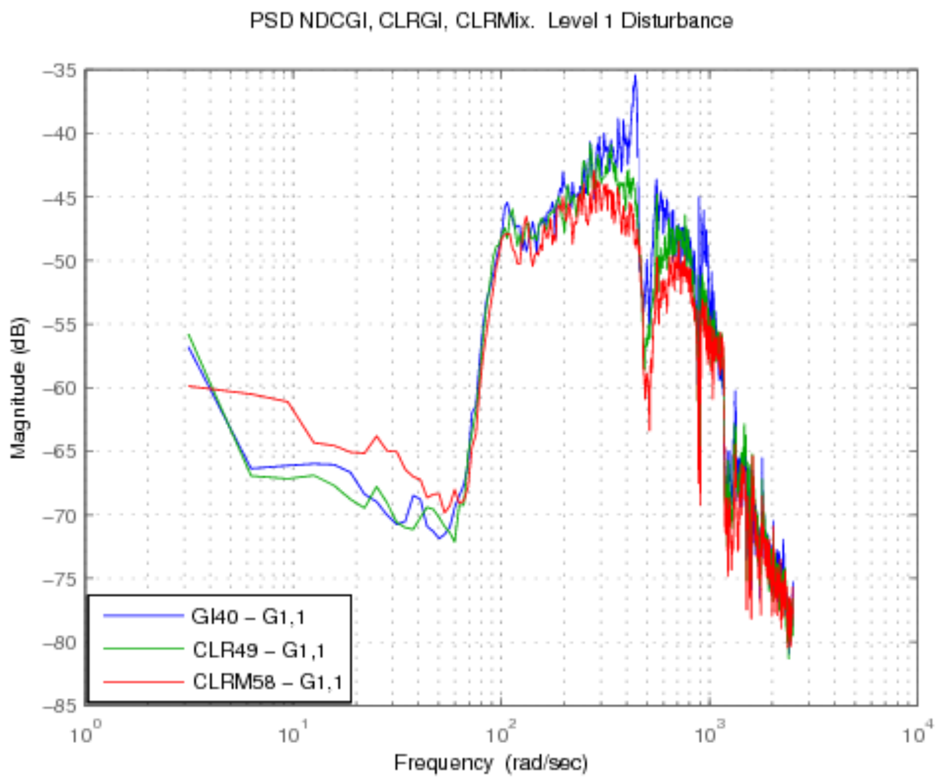
- A subset of U1 NDC paths are used to reduce loop modulus in very low U1
- Small reduction in disturbance rejection in the nominal condition is traded for improved behavior in the quiescent environment



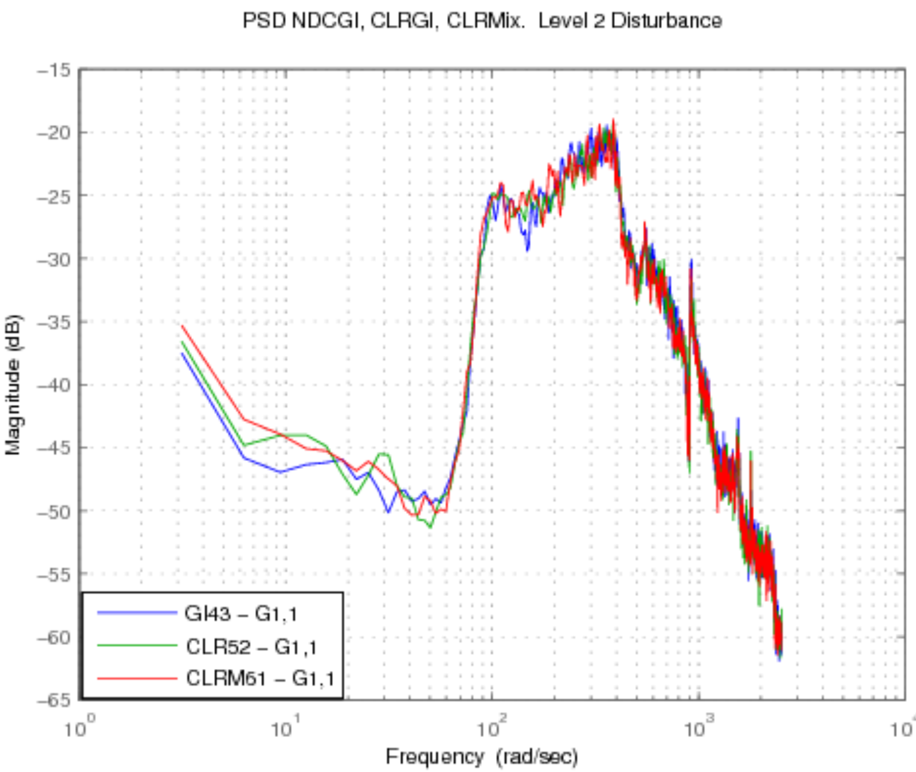
Level 0 Disturbance



Level 1 Disturbance



Level 2 Disturbance



Conclusions

- Large feedback systems
  - Good disturbance rejection
  - Sensitive to loop transmission variations
- Actuators in large feedback control applications
  - Expensive
    - Linear but fragile
  - Inexpensive
    - Rugged but imperfections cause oscillations in large feedback applications
- Multiple-Path Nonlinear Dynamic Compensation allows combination of imperfect actuators and large feedback

Investigators/References

- Grad Students
  - Dustin Carruthers (Left Hand Engineering)
  - Jeff Parkins (Well Dog Engineering)
  - Cameron Mock (Ball Aerospace)
  - Zachary Hamilton (Hiller Measurements)
- References

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  - Mock, C., Hamilton, Z., Carruthers, D. and O'Brien, J., "Nonlinear Compensation for High Performance Feedback Systems with Actuator Imperfections," 6th ASME Annual Dynamic Systems and Control Conference, Palo Alto, CA, October 2013.
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  - Sirlin, S and Laskin, R., "Micro-Precision Control/Structure Interaction Technology for Large Optical Space Systems," 5th NASA CSI Conference, 1993.
  - Spanos, J. and Rahman, Z., "Optical Pathlength Control on the JPL Phase B Interferometer Testbed," ," 5th NASA CSI Conference, 1993.